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The 2010 Gulf Coast Oil Spill

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Preface

This monograph (a preferable term here to 'book', I believe) was conceived after I had done a good deal of broadcasting, within the UK and internationally, on the Gulf Coast oil spill. Time is always limited in a broadcast, and facts and valid perspectives need to be got across succinctly to the exclusion of shallow comments which hardly leave a viewer or listener any better informed. I like to go to a broadcast having made a few jottings from news sources which as well as being possible material for the broadcast have attuned my mind to the topic shortly before I go on air.

If one is introduced in a broadcast as an expert an expert's view is expected and this will involve making and expressing judgements with a degree of originality without undue concern about how well they are received. In one of the earlier broadcasts I made on the Gulf Coast I was asked about the impact on bird life. I had no precise data on this, but replied that harm even to a single bird on the affected part of the Coast would be a sad event. I went on to add that huge numbers of birds are being killed all the time by flying into the wind turbines which have become so prevalent a feature of our landscape in the last few years and that that should be kept in mind when threats to bird life through an oil spill are being lamented.

By the time the spill was sealed and my services as a speaker on the topic were no longer required I had a deep sense of engagement with the matter and had had a number of ideas which there had been no opportunity to express on air. I also started to believe that there would be an important place for a fairly short (approximately 10500 words) monograph on the subject at this very early stage of a follow-up which will take time of the order of decades. I therefore contacted Ventus Publishing, who have published four previous titles from my 'pen', to enquire whether they would like to receive such a monograph and was pleased when the answer was in the affirmative.

To give a broadcast is a rewarding experience but might also leave one a little mentally fatigued. It is therefore always pleasant to receive after a broadcast a commendatory message from a listener or viewer. That has been my experience over about seven years of fairly regular broadcasting. After one particular broadcast on the Gulf Coast spill I received by e-mail a very warm message of praise from a colleague at Aberdeen which moved me deeply. I am sure that to name him would embarrass him, but I hope that he will be willing to regard himself as the anonymous dedicatee of this monograph.

My approach to writing this monograph has been a totally disinterested one, that is, I have no affiliation with any of the parties involved in the incident and have had no professional involvement with it beyond the media work which I have described. I have used only information accessible to anyone, and have made such judgements as I can on the basis of that in order to produce what I hope will be a useful synthesis. All such judgements were made in good faith.

J.C. Jones
Aberdeen
November 2010.

1 Background

1.1 General introduction

This part of the monograph will begin by considering the site of the leak, the Macondo field in the GoM[1] off the Louisiana coast. Let a reader be aware that the first significant offshore oil production was off the Louisiana coast in 1945. He or she should also be aware that the operation leading to the 2010 spill which is the subject of this monograph was exploratory drilling, not production. This makes comparisons with, for example, the 1988 Piper Alpha accident in the North Sea of doubtful validity. Piper Alpha was a production platform and hydrocarbon leakage began on the platform. By contrast, in the 2010 GoM leakage was from a well at a sea depth of approximately 1500 m. Discussion of the field will be followed by consideration of the drilling vessel Deepwater Horizon which was in service at the scene of the accident.

1.2 Macondo

Macondo is a ‘prospect’, that is, a site where a licence to drill for oil has been granted. The course of events if a prospect is successful is that an exploration well is followed by an appraisal well which in turn becomes a production well. Macondo is in the part of the GoM known as the Mississippi Canyon. There are both production and exploration activity within the Mississippi Canyon. Thunder Horse, one of the most productive oilfields in the GoM, is in the Mississippi Canyon. At Thunder Horse the sea depth is 1850 m (about 20% deeper than Macondo) and production is 0.25 million barrels per day with large amounts of associated gas [1]. There are four production wells at the field, which is operated by BP (75%) and Exxon Mobil (25%). The field occupies three ‘blocks’ of the Mississippi Canyon and is about 150 miles south east of New Orleans.

Drilling of Thunder Horse when it was just a prospect was in block 776 of the Mississippi Canyon. The block number having in recent months acquired notoriety is 252, as that applies to the scene of the drilling at Macondo where the accident occurred. In the GoM not all blocks are of the same size, although most are three square miles in area [2]. In the UK sector of the North Sea the convention is different and a block, a division of a quadrant, is an enclosure formed by 10 minutes of latitude and 20 minutes of longitude.

The Mississippi Canyon is just that – a subsea canyon – therefore significant depth variations of hydrocarbon activity are expected. Production in the Mississippi Canyon has been at sea depths varying from about 300 m for oil from the Cognac field operated by Shell [3] to in excess of 2000 m for gas (only) from the Aconcagua field operated by TotalFinaElf [4].

The process of creating an exploration well begins with drilling using a drill bit of wide diameter, between about nine inches and three feet. The drill bit will have either tungsten carbide or diamond (or both, if the bit is made from a polycrystalline diamond compact a.k.a. PDC) as the cutting material. As drilling takes its course and the well deepens successively smaller bits are used. A well having received the initial treatment with a wide drilling bit is said to have been 'spudded'. On October 21st 2009 the drilling vessel Transocean Marianas, on lease to BP, arrived at the location of Macondo in order to spud an exploration well. Drilling had to cease on 28th November when Transocean Marianas was taken out of service for repairs necessitated by Hurricane Ida [5]. Drilling was resumed in February 2010 when the vessel Deepwater Horizon, also owned by Transocean, arrived at Macondo. Drilling continued until the accident on 20th April 2010 which led to the deaths of 11 men and initiated oil spillage into the GoM.

1.3 Deepwater Horizon

It has been noted that the sea depth at Macondo was about 1500 m (> 0.9 mile). Immediately prior to arrival at Macondo the Deepwater Horizon had been drilling in a different part of the GoM known as the Tiber field. This was in a fairly modest water depth, but the Deepwater Horizon in that operation set a new record in well depth by creating a well of vertical dimension > 10500 m. The discovery of oil during this operation was seen as being on a huge scale, and will be discussed more fully subsequently. Drilling at the Macondo prospect by the time of the accident was also to a subsea depth of thousands of metres [6]. As a result of the moratorium imposed on drilling in the GoM shortly after the spill began, Transocean Marianas was transferred to Nigerian waters.

Deepwater Horizon was a semi-submersible rig and an outline of how a semisubmersible works [7] is necessary if the circumstances of the 2010 oil spill are to be understood. A semi-submersible has two hulls and when the rig is not in use or when it is being taken to a drilling site both hulls are occupied by air. As was the case with the Deepwater Horizon, the lower hull can have the catamaran structure comprising two 'pontoons'. These double up as a means of moving the rig when it is not in operation; when the pontoons contain air only they enable it to float and be propelled or towed. For drilling, the pontoons are filled with seawater and this causes 'submersion' but not to the extent that the outer hull touches the sea floor. Having been submerged to the degree required the rig can be held in place by anchors on the sea floor put in position by an anchor handling (AH) vessel. An alternative to anchorage and common in deeper water applications is dynamic positioning, whereby 'thrusters' provide as necessary equal and opposite influences to those which would have caused the rig to drift in water. Deepwater Horizon[2] was dynamically positioned [8] and its thrusters were rated at over 7000 h.p. The semi-submersible has become the most prevalent type of drilling rig, and the semi-submersible design is used not only in drilling but also, for example, in crane support. Deepwater Horizon[3] was built in Korea by Hyundai and was only ever used in the GoM. It took over two years to build. Had it not been for the accident Deepwater Horizon would have remained on lease to BP for another three years.

1.4 BP's involvement in the GoM

BP has an illustrious background of oil exploration and production in the GoM. The find at the Tiber field, briefly previously, is believed to have provided for access to oil in a quantity of the order of 5 billion barrels [9]. Additionally to BP, Petrobras and Conoco-Phillips [10] each had an interest in the Tiber field exploration. At the time of the discovery of the oil at the Tiber field in September 2009 – shortly before Deepwater Horizon was moved to Macondo – BP was producing about 0.4 million barrels of oil per day at its platforms in the GoM as well as engaging in exploration projects. The Thunder Horse field, also previously mentioned in this text and producing since 2008, was a BP discovery. Table 1.1 below gives details of some major BP exploration successes in the GoM. Comments follow the table.

Field.	**Details.**
Pompano [11]	Joint venture with Conoco. Commencement of production in 1994. Sea depth 570 m.
Marlin [12]	Situated 125 miles SE of New Orleans. Commencement of oil production 1999. Sea depth 990 m.
Horn Mountain [13]	Operated by BP (67%) and Occidental (33%) and productive of oil since 2002. Sea depth 1650 m.
Na Kika (a group of fields) [14]	BP and Shell each have an interest in the 'Na Kika project'. Production began in 2003 and is increasing as development continues. Sea depths in the range 1770 to 2300 m.
Holstein [15]	50-50 BP and Shell. Sea depth 1325m. Producing since 2004.
Mad Dog [16]	BP, BHP Billiton and Chevron all have an interest in this field, which is 150 miles from the Louisiana coast. Sea depth 1370 m. Producing oil since 2005.
Atlantis [17]	Discovered in 2002 and productive since 2007.
Thunder Horse	See sections 1.2 and 1.4

Table 1.1 Selected major oilfields in the GoM operated by BP.

Note the very modest sea depth at the Pampano field. Oil from this field has the disadvantage of a high cloud point, which can of course be an issue in 'flow assurance'. The Marlin field produces 60000 barrels of oil per day – about a quarter of the production of Thunder Horse – and also very significant quantities of associated gas. The Horn Mountain field, in blocks 126 and 127 of the Mississippi Canyon, is at a depth fairly close to the high end of the range for the Mississippi Canyon given in the previous section of this text. Its oil production is comparable to that of Marlin and its infrastructure is such that additions to it can be made if further exploration in that part of the Mississippi Canyon is successful.

The action of a semi-submersible was described above in an account of its function in providing a stationary base for drilling. A reader will appreciate that such a structure in situ for a longer period than it would be in drilling can be used as a production facility, and this is in fact the case in the fields comprising the Na Kika project (row four of the table). The Holstein field produces 0.1 million barrels per day of oil and large amounts of associated gas. The Mad Dog field (following row) is further from the Louisiana Coast than the group of fields comprising Na Kika. Production at Mad Dog is at 80000 barrels per day. The Atlantis field (penultimate row) is believed to contain 575 million barrels of crude oil, making it the third largest oil field as yet discovered in the GoM.

In summarising this section we note that the state of affairs immediately before the April 2010 accident was that BP was the largest producer in the GoM and accompanying their oil production is a correspondingly large quantity of associated gas. The exploration and production commitments of BP in the Gulf are on a huge scale.

1.5 Concluding remarks

This first part of the monograph leads into further ones in which details of the spill are analysed using such judgement as the author can make from information in the public domain. The initiating event at the spill was a gas explosion and this forms the subject of the next part.

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2 The Drilling Operation

2.1 Background

It was mentioned in the previous part of this volume that Deepwater Horizon was a semisubmersible, meaning that its base was some distance from the sea floor where drilling was taking place. The conduit enabling a drill mounted on the rig to be applied to the seabed is called a drill tube and, when the drill is in operation, the drill tube structure provides an exit for drilling mud[4] which, of course, at that stage contains drill cuttings. The initial job of spudding has already been described. During drilling a steel casing is inserted and this in effect provides an extension for the drill tube. What follows by way of cementing is standard procedure a description of which is attempted in the next section.

2.2 Cementing

The dominant element in oil well cement is calcium, present as silicates, aluminate and aluminoferrite [1]. These are all ionic compounds and constitute the clinker which comes from the cement kiln. Blending with gypsum – more calcium! – precedes milling to a suitable particle size. One cement can usually be distinguished from another by microscopic examination, and features so observed correlated with such properties as curing time (see below).

In the drilling of an exploration well cement is admitted to the steel casing, exiting at the bottom and moving upwards to form a coating ('sheath' in a Los Angeles Times article on the GoM accident [2]) on the surface of the casing isolated from the drill and from any hydrocarbon from the well. The flow properties of a cement can be improved by prior treatment with nitrogen to produce bubbles which disperse once the cement has contacted the outer surface of the casing. This is often described as giving the cement 'the consistency of shaving foam'.

After cement is admitted to a well as described in the previous paragraph time is allowed for the cement to cure, which involves reaction of the inorganics in the cement with water to form hydrates. Thereafter it provides a barrier to oil and gas egress from the well by any route other than the interior of the installed casing. A point missed by the LA Times article referred to is that although prevention of hydrocarbon exit outside the casing is an important function of the cement it is not the only one. Drilling fluid is used at such pressures as might possibly break the steel casing, in which event the cement will provide reinforcement.

Movement of the casing during cementing will clearly make for both displacement of the casing from its intended positioning and unevenness in the cement sheath formed. Such unevenness will make the cement sheath less effective. During cementing therefore the casing is held in position by devices called centralisers. The number of centralisers used will vary from one exploratory drilling operation to another but multiple centralisers are always used. This point is discussed further later in the monograph.

At the Macondo prospect cementing was performed by the Texas based company Halliburton [3]. Cement failure is a common cause of containment loss ('blowout') in the drilling of exploration wells. At the GoM accident in 2010, did the leaking hydrocarbon travel up the casing or around it? The latter case indicates cement failure. Inevitably this question was asked almost immediately afterwards and has been addressed in many discussions of the matter. Once a reservoir has been accessed the exploratory well is capped to await installation of production facilities if this is deemed appropriate after appraisal. The usual capping arrangement is two concrete blocks within the casing with a column of drilling fluid in between. The Macondo project had not reached that stage of development when the blowout occurred.

2.3 Analysis of some issues raised in respect of the drilling

The author has examined commentaries on the drilling operation made both during the leak and since it was stopped, and has gleaned information from what he sees as some of the most responsible and soundly based ones. This information is set out in tabular form below.

Reference.	Details.
[4]	18 of 39 blowouts in the GoM over a 14 year period attributed at least in part to cement failure.
[6]	The issue of the number of centralisers employed during the cementing raised by BP.
[7]	A few days after the leak started, a statement by Halliburton that cementing had been completed 20 hours before the blowout.
[8], [9]	Statements that BP had used fewer centralisers for the cementing than Halliburton had recommended.
[10]	Enquiries into the precise composition of the cement used.
[11]	Comments on BP's internal report into the accident
[12]	Condition of the Deepwater Horizon at the time of the accident reviewed.
[13]	The possibility that software failure led to the accident raised. Previous difficulties with software in oil drilling operations discussed.

The possibility that cement failure was the cause of the accident is strengthened by the information in row 1. Reference [3] raises a highly interesting point in addition to that noted in the table. It is well known that the seabed contains vast amounts of natural gas hydrates, that is, methane molecules enclosed in ice in a cage or, according to the terminology of structural chemistry, a clathrate structure. It is also well known that the curing of cement is accompanied by heat release. The question is posed in [3] of whether such an effect might have led to release of methane from hydrates. This matter has been further addressed; for example in [5] it is recorded that the National Academy of Sciences recommends avoidance of layers of natural gas hydrates in drilling for oil.

It is recorded in [8] and in [9] that BP used seven centralisers having been advised by Halliburton to use twenty-one. One must avoid superficial interpretations in such matters, even more assignment of blame on the basis of them. All sub-sea operations are subject to risk analysis. The frequency with which blowout will occur at the Macondo prospect would have been estimated as 10^{-n} per year, where n is likely to be in the region of 3 to 4, meaning once in every thousand to ten thousand years. There is no one way of calculating this frequency. A blowout can occur according to more than one sequence of events each of which will give a different value for the exponent 'n'. The calculations leading to a final value for 'n' will contain *inter alia* fractional reliabilities of components. These have a significant plus or minus, and two or more components might well be interactive so that loss of reliability of one affects the others. Whilst such interactiveness can of course be accounted for in risk analysis, all possible interactions in a multi-component system like a drilling rig will not necessarily have been identified. Two competent risk analysts could apply their expertise to such a system and obtain values of 'n' an order of magnitude apart. It might also happen that, notwithstanding the different 'bottom lines' of their respective calculations, the two analysts agreed that a major increase in the number of centralisers would not have a significant effect on the value of 'n'.

Use of the words 'might' and 'could' is inevitable in the preceding paragraph, imprecise though such terms are. The point being made is that an apparently startling statement such as that at the beginning of the previous paragraph – that a third as many centralisers were used as were recommended on the basis of a single risk analysis – is in itself no proof at all that this factor was the cause of the accident. If it is to be seriously argued that it was much further analysis, taking into account the design of the centralisers and their reliabilities, is required. Indeed arguments based just on the **number** of centralisers to the exclusion of consideration of their design and configuration and the materials from which they are made are very weak. Examination of the manufacturers' literature (e.g. [14]) reveals that there are many designs, and whilst some are made of alloys (in particular alloys containing zinc and/or aluminium) some are made in part of PVC [15].

The flawed reasoning in naive identification of **extent** of a particular feature (e.g., number of centralisers in the Macondo well) with safety can be understood by reference to the following simple example. Imagine that one is in possession of a valuable but very delicate antique ornament of a few centimetres maximum dimension. Its destruction through dropping on to a solid floor would involve irreplaceable loss and must be avoided. For it to be placed on display at the centre of a table of 1 m diameter would ensure its safety, and it would not be made any safer by increasing the diameter of the table from 1 m to 2 m.

The 'shaving foam' approach to cement insertion previously described was used at the Macondo prospect and in [10], which is dated 26th September 2010, the matter of the formulation of the cement is raised. There had been testing for stability at an independent laboratory of the 'mix' believed to have been used, and the matter of its stability after curing was addressed. The issue of cement performance is also raised in reference [11], following row of the table.

In reference [12] there is mention of possible defects in the Deepwater Horizon and an equivocal maintenance record. These are legitimate, indeed important, issues but again naive interpretation must be avoided. Parts of the Deepwater Horizon with a safety role will have been assigned a probability of failure. With age and 'wear and tear' this probability will increase and such increases can be incorporated into risk analysis. Their effect on the value of 'n' as defined previously can be quantitatively assessed and if the conclusion is drawn that they do not bring 'n' outside the range which usually applies in such operations no regulations are violated if use continues. One can be confident that figures for risk analysis relating to Deepwater Horizon when she was a new vessel in 2001 will have been revised since then.

The author has to emphasise that the apologia in the above paragraph, and the previous one which relating to the use of centralisers, are in no way defences of Transocean and BP respectively. Rather they are totally neutral attempts to point out that the significance of a particular act, omission or whatever cannot be understood without reference to risk analysis and this will usually be outside the scope of popular reporting.

2.4 Concluding remarks

This part of the monograph has given some emphasis to the cementing process which is certain to continue to be a point of importance as enquiries take their course, as is the condition of the Deepwater Horizon. One hopes that the respective roles and accountabilities of BP, Transocean and Halliburton will not dominate such enquiries to the exclusion of the retrospective application of engineering principles.

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Note added in proof.

On October 29th 2010 it was reported on news web sites that the composition of the cement mix was being looked into as a possible cause of the incident. A thought of the author's which, as far as he is aware, has not at the time of going to press been discussed is this. What was the pH of the cement? A cement for an oil well is usually in the range 5 to 8. For it to be too acidic will not affect the cement *per se* but will cause it to attack nitrile rubber O-rings. O-rings are used where the diameter of the casing changes because of changes in the bit diameter during drilling. The well at Macondo was deep, and that there were O-rings in use is almost certain but it is not known to the author what they were made of. There are many elastomers which have been used to make O-rings for oil wells not all of which are susceptible to acid attack.

3 The gas leak and explosion

3.1 Introduction

The leak was what in the terminology of hydrocarbon accidents is known as the 'initiating event'. It cost eleven men their lives, and its consequences were leakage of oil in the Gulf over a long period. The previous part of this monograph considered two possible reasons for the blowout: cement failure and release of natural gas from hydrates. During the media coverage of the spill, especially at the earlier stage, much was said about the blowout preventer (BOP) and the fact that it had been of no avail in this incident. The next section accordingly considers this.

The principal component of natural gas is of course methane CH_4. It is the first in the homologous series of organic compounds called alkanes (previously called paraffins): higher members of the series include ethane and propane and these might be present in small amounts in natural gas. Methane is the least reactive of all of the alkanes.

3.2 The blowout preventer

The function of a BOP is easily understood. It is placed between the drill tube and the reservoir and in the event that gas is released from the reservoir at high pressure it closes and prevents exit of the gas. If the device is not connected to a drill tube it still acts if there is a major pressure surge from the reservoir, in which event it simply closes a previously fully open hole. At the Macondo field the BoP was connected to the drill tube. The BOP, which was removed from the water for subsequent examination, weighed 300 US tons [1]. A BOP has many parts each with its own reliability of operation, expressible as a fractional probability, when required. Whether it is possible to trace failure of operation of the BOP to any one of the large number of interdependently functioning components will become clearer as the examination proceeds[5].

3.3 Passage of the gas along the drill tube

It is not known to the author what the internal well pressure of gas was. Values of 1000 p.s.i. (about 70 bar) are typical in newly drilled oil wells in which there is associated gas and it is thought that the pressure at Macondo might have been well in excess of this. That gas at such pressures should entrain some of the lighter components of the oil, perhaps up to about C_{10}, in behaviour similar to that of a 'gusher' is intuitively reasonable. Even if there was no such entrainment the gas itself at the well temperature would be likely to contain some hydrocarbons in the $C_2\rightarrow_4$ range which, in routine natural gas production, are usually stripped off as condensate[6] and incorporated into the liquid production stream. The question of the precise composition of gas reaching Deepwater Horizon is relevant to the fire and explosion behaviour as will be argued in the following section.

3.4 Events at Deepwater Horizon

There were 126 persons on board the semi-submersible when, at 21:49 Central Time (CT) on 20th April 2010, it experienced an explosion [2]. A point of major interest and importance is that there was an **explosion**, that is, combustion involving an overpressure. The low reactivity of methane has already been noted, and overpressure in methane combustion requires enhancement of reaction rate by certain factors. Such factors and their presence at Deepwater Horizon will be reviewed in turn. That the fuel contained higher hydrocarbons of greater reactivity than methane is highly probable as noted. The high internal pressure of gas at the well would have made for a high exit speed. This would have been reduced in some degree by friction on passage but even so entry into the atmosphere at Deepwater Horizon would have been rapid, making for turbulence and good fuel-air contacting. Each of these factors enhances combustion rate. Once gas having reached the Deepwater Horizon encountered its structural parts – walls, floors, beams – turbulence would have been increased further. These and machinery present would have led to a degree of confinement of the gas/air mixture once it was in the flammability range, and it is well known that confinement promotes overpressure. So the facts of the gas leak have in this paragraph been qualitatively linked with details of its consequences.

There remains the question of the origin of the ignition source, and some background from basic combustion science is necessary of this is to be discussed effectively. Texts on combustion science often contain values of the 'minimum ignition energy' of a particular gas-air or vapour-air mixture and these are of the order of millijoules. In other words a spark of that quantity of energy or higher would ignite the mixture whilst one of smaller energy content would not. That on an empirical basis minimum ignition energies have been useful in such matters as flammable liquid storage is not in doubt, but neither is the fact that 'minimum ignition energy' so understood is unsound. There can be no minimum ignition energy for a particular gas-air mixture because whether a specified amount of energy will ignite the mixture or not depends on how quickly the energy enters the mixture. Heat transfer from spark to mixture takes time, and the more rapidly a quantity of heat is transferred the greater its effectiveness as an ignition source. This leads to the concept of 'ignition energy at instant release', that is, the amount of energy which if transferred instantaneously into a mixture would ignite it. This would be a correct definition of 'minimum ignition energy', but it is a hypothetical quantity only as instant release cannot be realised. However, the minimum ignition energy so understood can be estimated by determining ignition energies across a range of release times and extrapolation, though few such estimates have ever been attempted.

The author's view of how ignition sources arise in situations like that at Deepwater Horizon is as follows. Quantities of heat orders of magnitude higher than millijoules are of course being transferred everywhere all the time. Imagine that the enthalpy at a point in the atmosphere where the temperature is constant was plotted as a function of time. Notwithstanding the isothermal conditions the plot would have blips above and below the line signifying the enthalpy of air at the fixed temperature. This is because of continual arrival and departure of heat from the site as noted, and these would (as also noted) be of higher orders of magnitude than millijoules even though their effects were only 'blips' in the enthalpy. In a gas the thermal inertia would be low enough for such blips to have no measurable temperature effects.

Now imagine such a situation experiencing the perturbation of entry of another gas (in the case of Deepwater Horizon natural gas) at high speed and with a high degree of turbulence. This would not only exacerbate the 'blip' effects previously noted but would quite conceivably lead to a blip of sufficiently high amplitude and short duration to be an ignition source according to the principles of ignition discussed above. Obviously such occurrences are random and in the event that ignition was by this mechanism the 'ignition source' would be totally untraceable. If (as is quite possible) the natural gas was initially at a temperature higher than that of the air which it encountered this effect would occur all the more easily.

The explosion which occurred on April 20th at 21:49 has therefore been analysed in this section with as much precision as is possible from the information obtainable. After the explosion fire developed and propagated and on 22nd April at 10:22 Deepwater Horizon sank after another explosion overpressure from which was probably the cause of structural failure. The surprisingly long period between the initial explosion and final sinking is probably due to the application of water by several extinguishment vessels. Usually at a fixed offshore installation (which of course Deepwater Horizon was not, although the comparison being made is reasonable) the event signified by the message 'PLATFORM LOST' occurs only a few hours after the initiating event.

3.5 Injuries and deaths

It is reported [3] that fatal injuries at Deepwater Horizon numbered eleven and non-fatal injuries seventeen. A total cohort of twenty-eight as the basis of the reasoning which follows is a small one. It is recorded in [4] that those killed are 'believed to have been working in the area of the explosion believed to have caused the rig's loss'. Accordingly it is taken for the purposes of this discussion that injuries and deaths all occurred as a direct result of the fire and explosion. That means that the injuries for which the fire and explosion were responsible were 40% fatal and 60% non-fatal. With such a small 'sample' this approximates to about equal fatal and non-fatal injuries. Usually when overpressure ('blast') is the factor causing death and injury there is an order-of-magnitude difference between the number of fatal and non-fatal injuries, whereas when heat is the factor the fatal and non-fatal injuries occur in approximately equal numbers. This argument cannot be totally accepted without consolidation requiring details in relation to the GoM accident which the author has been unable to obtain and which might not be known even to those professionally involved in the follow-up with unrestricted access to information. A preliminary case has however been made that even though there undoubtedly was an explosion the factor causing death and injury was not the blast but the heat. Here is a possibly fruitful line of future formal investigation.

In section 2.3 it was stated that the frequency of occurrence of the initial leak could be expressed as 10^{-n} per year and that as a rough estimate 'n' would have a value of 3 to 4. This can be analysed a little more fully as is shown in the shaded area below.

We utilise the equation [5]:

$$N\varphi(N) = 10^{-n}$$

where $\varphi(N)$ is the frequency of an event involving N deaths and 'n' is as previously defined.

Applying to the Macondo accident in which there were 11 deaths and using a mid-range value of 3.5 for n:

Frequency of an accident involving 11 deaths = $10^{-3.5}$ year^{-1} or one such accident every $10^{+3.5}$ years = 3150 years.

11 deaths in 3150 years converts to 1 death about every 300 years.

3.6 Concluding remarks

The immediate, and deeply tragic, initiating event at the Macondo field was gas leakage. The matter of payments to the injured and to the families of the dead is very much in the news at the present time. This was the only event during the entire leak which involved loss of human life. It was followed by escape of oil into the sea and this is covered in the further parts of this monograph.

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4 Crude oil release

4.1 Introduction

The obvious result of the combined events of severance of the drill tube and failure of the blowout protector was discharge of crude oil into the sea. By a week after the initial event, by which time Deepwater Horizon had sunk, estimates on the leakage rate were being put at 5000 barrels per day [1] from more than one site in the damaged structure. It is however important to understand that at any scene of offshore oil production there will be a background level of oil in the sea water even when nothing is amiss. One reason is that seawater having exited the wellhead/platform interface ('Christmas tree') at a production platform is never totally cleansed before being put back into the sea (see table below). A more important one is natural seepage from subsea reservoirs which, it is believed (e.g. [2],[3]), accounts for something like half of the oil content of the sea[7]. Oil from production and transportation activity therefore adds to this. A discussion on background levels of oil in the sea follows.

4.2 Background levels of oil in the sea

A major source of leakage of oil into the sea is tankers which receive oil from a production platform or from a offloading facility. It is arguable that globally oil tankers contribute more to discharge of oil into the sea than do offshore production facilities. This is not due simply to leakage but also to the periodic cleaning of the tank interiors. In this regard let it be remembered that a 'supertanker' holds of the order of a million barrels and travels, in a single voyage, thousands of kilometres. The table below gives some figures for measured or estimated levels of oil in the sea. Comments follow the table.

Location and reference.	**Details.**
North Sea: water having been separated from oil for return to the sea [5].	40 p.p.m. of oil aimed for but not at this stage a statutory maximum.
Gulf of Guinea, West Africa [6].	>10 p.p.m.
Bass Strait [7]	8p.p.m. background, peaks some as high as 50 p.p.m.
Bay of Bengal [8]	1.5 to 4.2 p.p.m.
Off Mumbai [8]	Up to ≈ 40 p.p.m.

Parts per million in such applications is on a volume basis, that is 1 p.p.m. is a cm^3 of oil in a m^3 of seawater. If it is thought of as being on a weight basis there are inaccuracies, probably not major, in comparison with experimental measurement errors, due the difference in density between oil and seawater. Part of the Gulf of Guinea (row two of the table) is Nigerian territory, and Gabon also has a coastline at the Gulf of Guinea. The oil industry in these countries has been adversely affected in safety as well as in business terms by corruption and violence. The levels of oil in the Bass Strait are at about an expected background level but have displayed marked variations of about 20 p.p.m. and even a few up to 50 p.p.m. as reported in the table. Oil production in the Bass Strait, off south eastern Australia, began at the same time as oil production in the North Sea. The question of possible exploration for in the Bay of Bengal is a controversial one. The fairly modest levels there at the present (row four of the table) arise from entry of contaminated water at estuaries along the Bay. There are of course oilfields off Mumbai and the much higher value of the oil concentration off this part of the coast of India (final row) reflects this.

Broadly speaking one expects oil levels in the sea to be p.p.m. or a few tens thereof. How far in the event of leakage such as happened in the GoM the level exceeds that is a key issue in assessing possible consequences. It was reported ten days after the leak began [9] that just over half a million litres of dispersant had by then been applied to the affected part of the GoM. Oil discharge by then must, on the basis of the figure given in a preceding paragraph, have been five to ten million litres. Additionally to the use of dispersants there was some skimming of the oil.

4.3 Plumes

The word 'plume' has occurred widely in reports of the GoM leak (e.g. [10]), with more than one meaning. The most common meaning is oil beneath the surface of the sea and unable to rise to the surface because of water movement[8] which exceeds the buoyancy effects due to the lower density of oil than seawater. Plumes have been observed close to the spill and some distance from it in which case they cannot be unequivocally attributed to the spill. In some such plumes the oil concentration has been as low as 0.5 p.p.m.

Dispersants and skimming have already been discussed as mitigation measures. An important means of removal of oil in a plume is microbial degradation and this has been commented upon several times (e.g., [11], [12]). Such microbes occur naturally in suspension in the sea and also on seabed surfaces, and their 'staple diet' is oil having seeped naturally from reservoirs or leaked from tankers. Microbes capable of breaking down oil include *Oleispirea antarctica, Oceaniserpentilla haliotis* and *Thalassolituus oleivorans* [13]. There are two sides to the matter of microbial involvement in mitigating the leak. One, obviously, is the extent of such mitigation. The other is the strongly modified ecology which the microbes capable of breaking down the oil experienced as a result of such a major spill and its effects on their proliferation and performance. It has been reported [14] that proliferation of such microbial cells resulted from the existence of plumes and , more interestingly, that a previously unknown species of microbe has been observed to be breaking down the oil. Full characterisation of this is awaited but it is thought that it is of the genus *Oleispirea*.

4.4 Spillage rates

'Time zero' has already been given as 21:49 on 20th April. Because of the success if 'Top Hat 10' (see section 5.7) oil discharge into the sea ceased at 15:25 on 15th July [15]. There was much uncertainty and conflict of information over the leakage rate. Published estimates of the daily release rate over the duration of the spill are given in the table below. In the final column is the flow rate multiplied by 87 days, the corresponding value of the total amount released.

Authority and reference	Release rate/barrels per day	Total amount released between 20th April and 15th July/barrels
Department of Energy [15]	60000	3 million
BP, 'worst case' [15]	100000	5 million
Associated Press [16]	100000	5 million

The contrast between the release rates in column two and that quoted from [1] for the very early stages reflects acceleration of leakage which, it is known, did occur.

4.5 Further remarks

The most important such 'remark' is that large amounts of natural gas accompanied the oil having leaked. As early as May 11th [17] the observed behaviour of the slick above the leaking well was attributed to a change in the gas/oil proportions of the leaking hydrocarbons since the leak began. The gas of course does not contribute to the slick but simply enters the atmosphere. There was burning of some of the gas released in the GoM accident and this will be considered when responses to the spill are discussed.

A point which the author made in a BBC interview will be reiterated here. Comparisons of the GoM accident with Exxon Valdez are better avoided. At the 1989 Exxon Valdez accident [18] about a quarter of a million barrels of crude were discharged from a supertanker into Prince William Sound, Alaska. Exit of the oil was by gravity: at the recent GoM accident it was by pressure of associated gas in a subsea well. The mechanics were so different in the two cases that comparisons are unhelpful if not potentially misleading. This is being emphasised because such comparisons were made in the media, especially at the early stages of the GoM accident.

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5 Responses

5.1 Introduction

It was not until 24th April that it was confirmed with the use of ROVs[9] that oil was leaking from the well at the Macondo prospect. [1]. By April 26th there was a slick of estimated area 26800 square miles [1]. By 30th April the release rate of 5000 barrels per day given earlier in this monograph as the release rate at the earlier stages had been reached. The various measures which were taken will de described.

5.2 Booms and skimmers

By April 29th booms and skimmers were, at the direction of the Federal Government, in use at the scene of the leak. The active agent being a polymeric substance, an oil absorbent boom is capable of taking up about 25 times its own weight of spilt oil. Polypropylene sheet foam, and its polyethylene analogue, are common choices of absorbent in booms and manufacturers of such materials had to have extra shifts to meet the demands of the GoM spill [2].

A skimmer is a device which once attached to a vessel removes oil on the sea by suction. A simple, privately owned recreational vessel can be adapted into a skimmer boat provided that there is either a fixed or a floating receptacle to receive from it oil once removed from the sea [3]. The initial action of a skimmer boat is to concentrate ('corral') a slick with booms and in so doing reduce its surface area. The oil once skimmed is transferred to a barge, and will be directed not to its hull but to portable containers which can be 'rolled off' so that the action of the skimmer-barge pair is not restricted by a need to empty the barge. The containers can of course be taken ashore by a further vessel. Additionally to this *modus operandi*, which is likely to be followed only in calm waters, a heavy oil tanker can be used in skimming. Oil received can be stored in the tanker space and water separated from it returned to the sea. There were offers, for example from the Netherlands [4], to make 'skimmer arms' for attachment to vessels available in the GoM emergency and such devices from Canada were also used.

5.3 Activity of the Discoverer Enterprise

In mid-May the drilling vessel Discoverer Enterprise [5], also a Transocean rig, arrived in the GoM. It was used to receive oil from the spill, and a burner was mounted on it for the flaring of natural gas accompanying the oil[10] [6]. Some of the oil was also flared whilst some was collected and taken ashore for refining. Later the vessel Q4000, also a semisubmersible and registered to the US, came to the scene and itself fulfilled and oil/gas collection and flaring role. These endeavours provided for significant mitigation of the oil leak. There were by this time many vessels at the scene in readiness for the further measures which were to follow.

5.4 The metal dome

A 100 tonne (approximately) dome was fabricated and placed over the leak on 7th May. Made of steel and concrete and the height of a four storey building, it was taken by barge from Port Fourchon LA to the scene of the leak. Its installation with a crane involved movement of one metal surface over another with the possibility of frictional generation of a spark. For that reason the operation was initially postponed because of the stillness of the weather conditions and resulting build-up of vapour from the spill. It was considered safer to proceed once there was a considerable speed of wind providing for removal of vapour [7].

The purpose of the dome was to restrict oil dispersion within the sea and to divert oil to a funnel for collection on to a vessel. By 17th May it was clear that this had failed as a result of a factor well documented in offshore engineering generally. Passage of the accompanying gas through the funnel, which acts as a nozzle, caused its thermal energy to be converted to kinetic. The consequent cooling of the gas led to reaction with water vapour to form natural gas hydrates and this resulted in blockage. As already explained these hydrates occur naturally and very extensively on the sea floor and on continental shelves, and they are seen as a major potential fuel for the 'beyond oil' era. Their formation during oil and gas handling is a widely observed phenomenon and an issue in pipeline reliability. It was the reason for the failure of the dome.

5.5 Top kill

Crude oils are invariably less dense than water and drilling fluids, which are suspensions in water as such substances as clay ('bentonite') and haematite[11], are always denser than water. In this section the role of drilling fluid in stopping previously uncontrolled oil movement will be outlined. Passed down the drill shaft, a drilling fluid ('mud') lubricates the drill bit and removes drill cuttings which will be carried in the exit flow.

If a crude oil naturally flowing in one direction encounters an opposite flow of drilling mud it is an unequal contest and stoppage or reversal of the oil flow is expected. This is the basis of 'top kill', and such an operation began at the scene of the GoM oil leak on 26th May [8]. The Q4000, also involved in receiving and flaring hydrocarbon from the leak as noted, had a role in the top-kill operation by holding the pipe through which the drilling fluid was to be passed for injection into the well. 50000 barrels of the fluid – an intentional overestimate – were available for the operation [10]. Pumping capacity was 30000 horsepower[12].

The idealised action of a top kill operation given in the first two sentences of the preceding paragraph could be demonstrated very easily in laboratory simulation using simply a U-tube, oil being admitted to one limb and drilling fluid to the other. In a real top kill operation there are many other factors. The fluids will go deeper into the drilled well than the installed casing, so channelling or absorption of the fluids are possible. The oil and drilling fluids have different viscosities and the drilling fluid, being a suspension, is non-Newtonian in its behaviour. In the top kill attempt under discussion the appearance of the drilling fluid in the drill tube which had been the initial exit route for the oil was seen as being inauspicious. It was announced on 30th May that this attempt to top kill the leaking exploration well had not been successful [12]. This was in spite of an additional 'junk shot' [13] in which golf balls and shredded tyres were injected with considerable velocity into the well. One purpose of this was to provide a vertically downwards pathway for the drilling fluid. By the time the top kill was declared a failure 30000 barrels of the drilling fluid initially available had been used.

The top kill attempt post-dated the beginning of the drilling of relief wells in the hope that success of the former would eliminate a need for the latter. This is further discussed in the following section. Meanwhile the reader should be aware that there are functions of drilling fluid during standard operations that are not relevant to drilling per se. Whenever a rig such as Deepocean Horizon is in operation there is a need to stabilise fluid flow, or prevent uncontrolled fluid flow within an assembly comprising the rig itself and its links to and from the sea floor. Drilling fluids find an important role here and the only relevant property of the fluid is density: viscosity is unimportant if there is no lubrication function or removal of cuttings. Seawater is about the same density as some drilling fluids and can be used in their place, with obvious economic benefit, in such roles. That this was so in part of the drilling structure at Macondo was noted [14], [15].

5.6 Relief wells

Transocean's Development Drill III [16] entered the picture on 2nd May [17], [18] when it began work on a relief well. This of course required 'spudding' in the same way that the well at the Macondo prospect did. The relief well was to be drilled at a depth of 4000 m below the seabed to intercept the original well. After such interception drilling fluid can be admitted, followed by cement. Work on a second relief well began on 16th May using Transocean's Discoverer Enterprise rig. The physics of relief wells is similar to that of top kill in that is simple opposition of the flow of one fluid by another, but once the relief well is constructed circumstances are much more controlled than they are in top kill. On the other hand time of the order of weeks is required for a relief well to be drilled.

5.7 'Top Hat 10'

This was smaller than the first container dome which had failed through hydrate formation as noted above. It was put in position on 12th July [19] and used antifreeze to prevent hydrate formation [20]. Once in position it contained oil leaked from the damaged well and enabled it to be transferred to a vessel. Four days later BP announced that release of the oil into the GoM had stopped. It was very good news that oil leakage had been contained, but there could be no cessation of emergency response until it was finally stopped and this required completion of at least one of the relief wells.

5.8 Closure on September 16th

On this date one of the relief wells made its intended intersection with the exploration well where the trouble had begun. By that time the site of the initial leak had been sealed with cement (that is, from the top) but the closure was not regarded as complete until there had also been sealing with cement from below via the relief well. On September 17th cement entry into the relief well began and once the cement had cured a permanent lasting closure had been achieved.

5.9 Concluding remarks

In this part of the monograph the measures taken over the 87 day period of the spill have been briefly recounted. Emphasis has been on the scientific principles, for example of the action of a boom and of top kill. The well is now one of about 27000 'plugged and abandoned' wells in the GoM. What the future might hold relation to the incident will be discussed in the postscript which follows.

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Postscript

The Gulf Coast oil spill will have a place in history as one of the major disasters of the early 21st Century. The follow-up will be over many years as will the settlement of claims for damages. Policymakers in the matter of exploratory drilling might well be influenced. The companies concerned have reputations to restore. There are also the relatives of the 11 dead to be thought of.

Exploration for and production of oil have been a major factor in world affairs for over a century and the current need to address greenhouse gas emissions has introduced a new dimension to this activity. The world needs 80 million barrels of oil per day. Substitution of carbon-neutral fuels for oil, and of such things as wind farms, will be limited even if targets for such substitution over the next decade or so are met. There is a revival of interest in coal, both for burning as such and for conversion to gaseous fuels. Well and good, but let the hazards of coal mining be understood. One of the most 'energy hungry' nations in recent years has been China, where the safety record of coal mines is lamentable. In 2004 (the most recent year for which the figure is obtainable) over 6000 coal miners in China lost their lives whilst at work. Even in countries where safety standards are much higher, fatal accidents in coal mines occur. An example is the accident at the Sago Mine in West Virginia in January 2006, when 12 men died. So replacement of oil by coal or coal products, advantageous though it might be in some particular combustion applications, is not promising in safety terms.

It is inevitable that following the recent GoM accident questions will be asked about offshore safety generally. One has been the safety of 'plugged and abandoned wells'. Once the well at the Macondo prospect had been classified as such there was a surge of interest in plugged and abandoned wells in the offshore oil fields of the world and an expression of concern about their safety. The author was in fact asked to prepare a statement for the media on this, and the statement is attached as an appendix to this monograph. It addresses the matter of plugged and abandoned wells per se but, more importantly, is intended to get across the point that a spin-off issue like this is not potential news and that once a balanced appraisal has been made its irrelevance to the primary issue – in this case the GoM accident – might well become clear.

Many will be following with close attention the events following the accident. Without doubt many books will be written on it as new information becomes available and the deliberations and decisions of the formal enquiry unfold. One of the most important points in any litigation is identification of damage due solely to the recent incident having regard to the fact that there has been oil production of the Louisiana coast since 1945. The author reiterates the hope expressed in the preface that a discussion the length of this one in the very early days after the accident will perform a useful role.

Appendix

Media statement on plugged and abandoned exploration wells released in early October 2010.

An exploration well will be plugged and abandoned after it has been judged that it will not if developed further yield enough oil and/or gas ever to become the scene of production. There are about 27000 abandoned exploration wells in the Gulf of Mexico, some of which are not in the strict sense 'plugged' since exploration at them was never finally terminated only suspended. Less stringent procedures apply to sealing practices for these than apply to a permanently abandoned well. A well does not become ownerless after abandonment and responsibility for it continues. Since the Gulf of Mexico oil spill from April to July this year concern has been raised about the possibility of leakage through abandoned wells. The following points will be made in relation to this.

There is monitoring of the condition of plugged and abandoned wells and resealing where it is believed necessary. The thoroughness of such monitoring varies according to the local regime. That a particular well has been in plugged and abandoned state for a long time is not in itself cause for alarm. A risk analysis, the bottom line of which was that probability of loss of containment of hydrocarbon from the well was very low, would have been applicable when the well was newly plugged. With the passage of the years the reliability of whatever materials were involved in the plugging will have been reduced, but not necessarily to a stage where the probability of leakage is, according to standards applying at the scene of the well, unacceptable. A risk assessment along these lines can be carried out for a very elderly abandoned well in relation to which concern has been expressed and a judgement as to whether resealing or whatever is necessary made on the basis of it. The gist of this advice is that age alone does not preclude adequate containment by a well. This is NOT equivalent to saying 'Let well alone'!

If there is to be major discussion of the possible hazards of plugged and abandoned wells a comparison with natural seepage of oil from subsea reservoirs is necessary. In the oceans of the world, natural seepage accounts for a half or more of the background oil content. So in any large expanse of water such as the Gulf of Mexico or the North Sea the possibility of contamination from abandoned wells needs to be considered alongside natural seepage. It must also be remembered that when a well is plugged and abandoned precisely specified practices must be followed and documented. This will be the case in the very near future when the well at the Oates prospect in the North Sea is plugged and abandoned.

That the matter of leakage from abandoned wells has been raised after the recent Gulf of Mexico incident is natural and there should be a greater awareness of it is all to the good. Let a reader experiencing such awareness take note of the points I have made.

Endnotes

1. This abbreviation for Gulf of Mexico will be used throughout.

2. It has been argued that in maritime law a dynamically positioned unit is an 'anchored vessel', in which case anchored simply means 'stationary'.

3. A reader wishing to see a colour image of the Deepwater Horizon should go to http://budsoffshoreenergy.files.wordpress.com/2010/04/deepwater-horizon.jpg or equivalent.

4. a.k.a. drilling fluid or drilling gel.

5. It is stated in: http://www.theinfomine.com/2010/05/13/what-caused-the-bp-oil-spill-in-the-gulf-of-mexico/ that in 2001 Transocean identified 'more than 260 things' that can go wrong with a blowout preventer and cause it to fail.

6. a.k.a. natural gas liquids (NGL).

7. The scene of the largest marine hydrocarbon seepage in the world is Coal Oil Point, which is in the Santa Barbara Channel [4].

8. 'Marine wave energy' can be the basis of electricity generation for communities.

9. Remotely operated vehicles.

10. For a vivid illustration of this operation go to: http://www.boston.com/bigpicture/2010/05/oil_reaches_louisiana_shores.html

11. There are such things as oil-based drilling fluids. These are less prevalent that water-based ones and are usually restricted to onshore use [9].

12. The power is given in [10] as 30000 hydraulic horsepower. It is shown in [11] how mechanical and hydraulic horsepower are equivalent and that one unit of either is equal to 746W. The pump capacity at the scene of the top kill was therefore about 20 MW.